ANTHROPOMETRIC ACCOMMODATION OF FEMALES IN CANADIAN FORCES AIRCRAFT CREW STATIONS

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SUMMARY

To ensure physical accommodation of humans in aircraft crew stations, aircrew traditionally have been selected on the basis of specific standards. To be effective, these standards must be based on anthropometric limitations imposed by actual crew stations. Evidence suggests this generally is not the case. Instead, selection standards have frequently evolved from (1) aircraft design recommendations, which often bear little relationship to the finished product, or (2) anthropometry of existing aircrew, which ignores the issue. Recognizing this problem, the Canadian Forces (CF) has undertaken a large-scale study known as ACCE (Aircrew/Cockpit Compatibility Evaluation). A computer-based modelling strategy was developed to determine anthropometric limitations, on a crew station by crew station basis, and their subsequent effect on accommodation of pilot and navigator populations. The approach is attractive because it encompasses possible multivariate relationships between anthropometry and crew station geometries, and it is sub-population independent; it assumes a *human* anthropometry but is blind to gender, nationality and race-specific differences. The flexibility of this strategy has allowed assessments of *fit* for both female and male populations in two CF aircraft — the CT133 utility jet and the CH136 light observation helicopter. Results show that current CF selection standards do not represent the range of anthropometry these aircraft can accommodate. This leads to biases in selection against females and small males.

1. INTRODUCTION

In the interest of flight safety and mission success, physical incompatibilities between pilots and crew stations should be avoided. Each pilot must be able to meet operational requirements for reach, vision and body clearance at one or more configuration of the seat and the rudder/rotor pedals. For an existing fleet of aircraft, this objective can be met by selecting aircrew appropriately. But to be effective, the criteria for selection must be based on anthropometric limitations imposed by individual aircraft types. Although this is a case of *fitting the pilot to the aircraft*, it cannot be avoided as long as differences among crew station geometries are as prevalent as their similarities.

Use of anthropometry for guiding selection implies that anthropometric limitations imposed by aircraft are known. Yet, relatively little information of this sort is available. A popular assumption is that anthropometric limitations of aircraft are contained within their design specifications. However, this assumption is false due to the realities of aircraft design. Designs can change significantly throughout the design process, making it difficult to assess eventual aircrew accommodation. Only fitting trials can determine if anthropometric design criteria truly have been met.

Even if initial design criteria are met in the finished product, the external validity of the criteria can be suspect. In most cases human anthropometry is described by a limited number of static (i.e., non-interacting) dimensions. It has been shown that such dimensions (e.g., 5th to 95th percentile stature) fail to adequately represent composite human anthropometry [1]. Also, such criteria are often based on particular population parameters: parameters which may change with time (e.g., increases in mean stature) [2].

The most reliable selection method is a *live* fitting trial in which a candidate is physically placed within the crew station. The method is attractive because it is conclusive; it tests the unique physical characteristics of the individual, accounting for effects of clothing and personal equipment, with little or no data analysis [3,4]. However, due to a number of disadvantages, not the least of which is expense, the method usually is not feasible as a universal selection tool [5]. Other strategies are therefore used to select aircrew. The most common selection criteria are minimum and maximum acceptable limits for several anthropometric dimensions [6].

The use of such criteria to select CF aircrew originated in 1966. At that time, several critical incompatibilities between body dimensions of aircrew and geometries of aircraft became evident [7,8]. It was decided that anthropometric standards would be used to screen aircrew candidates and that, until operational requirements dictated otherwise, these standards would be based on results of a 1962 anthropometric survey of Royal Canadian Air Force male personnel [9]. First and 99th percentile values for mass, stature, seated height, thigh length and leg length were used to derive body size ranges for aircrew candidates. Extra tolerances of 2 cm were added to the limits, effectively extending acceptance beyond the dimension ranges of the aircrew population surveyed [10]. Ironically, this strategy ignored the original incompatibilities for which anthropometric selection criteria were deemed necessary in the first place.

With minor modifications, current CF selection criteria are based on those 1966 standards (Table 1). Also, the CF maintains a recruiting policy of *universal assignability*: successful pilot candidates, whether male

or female, must be able to operate any CF aircraft. Considering the origins of the selection criteria and the variability of CF aircraft (with respect to origin, age, size, mission and configuration), the CF accepts aircrew candidates who do not *fit* all CF crew stations [11]. On the other hand, it may reject candidates suitable for all or many of the aircraft. Given that the CF now employs female aircrew, such errors will become more common.

The CF selection standards have been defended on the grounds that they do not differ significantly from the standards of nations which supply CF aircraft [6]. However, in an advisory publication on the topic, the Air Standardization Coordinating Committee (ASCC) has recognized the need to know anthropometric limitations of aircraft, especially as they relate to aircrew/cockpit compatibility and successful exchange of aircrew amongst different military forces [6]. This publication tabulates differences in national aircrew selection criteria and minimally identifies known anthropometric limitations for some crew stations. For a substantial number of aircraft cited, anthropometric limits have not been set. It is therefore imperative that empirical studies be performed which map the anthropometric limitations unique to each aircraft.

Results from such studies could have direct implications for pilot recruitment policies. For example, enforcement of universal assignability using standards that are based on aircraft-imposed limits could severely restrict the number of pilot candidates selected. In fact, the limitations may necessitate mutually exclusive selection criteria for specific aircraft, or show clusters of aircraft that impose similar anthropometric limitations. Such findings could force policies where a pilot's career must follow specific aircraft assignments, or even suggest specific aircraft assignments for sub-sets of the pilot population (e.g., males versus females). Assignment of pilots to international aircrew-exchange programs could also be affected.

	Pilot		*Navigator*	
Dimension	*Min (cm)*	*Max (cm)*	*Min (cm)*	*Max (cm)*
stature (standing height)	157.7	193.1	157.7	193.1
seated height	86.4	100.3	85.1	101.6
buttock-heel length (leg length)	99.6	123.2	99.6	123.4
buttock-knee length (thigh length)	54.6	67.3	54.6	67.3

TABLE 1. CF Aircrew Anthropometric Selection Standards.

The CF accepts that aircrew selection must take into account physical restrictions imposed by crew stations. Hence, it has initiated an Aircrew/Cockpit Compatibility Evaluation (ACCE) to determine anthropometric limitations imposed by CF aircraft. The scope includes all pilot and navigator crew stations since information currently available has come from investigations of specific compatibility problems identified by existing aircrew [12-15]. The results of ACCE are being used in a review of CF aircrew selection standards. This paper offers results from evaluations of the CT133 and CH136 pilot crew stations, performed in support of that effort. For the purpose of this paper, emphasis is placed on describing the differences between two populations (males and females) in each of the two crew stations.

2. STRATEGY

Several obstacles needed to be overcome for ACCE. First, no prescribed method for evaluation was available. Second, evaluation criteria and operational assumptions (e.g., effects of clothing, personal equipment, etc.) had to be established. Third, aircrew task performance criteria for reach, vision and clearance had to be determined. Fourth, critical dimensions of CF crew stations had to be measured and represented in a usable form.

Selection of the Evaluation Tool

Traditional methods for assessment include (1) use of live subjects, anthropometric dummies or partial manikins in real or mock-up environments, and (2) comparison of 2-dimensional drawing board manikins with engineering drawings. These methods were rejected because they do not adequately represent variable anthropometric combinations. Availability, validity, feasibility and cost were other factors that precluded selecting these techniques [16].

Three-dimensional computer modelling was chosen as the primary evaluation tool for ACCE. Depending on the system employed, this tool can be used to model complex individual differences and simulate atypical body structures and functions. Computer graphics and mathematical algorithms can be used to construct and manipulate 3-dimensional human models within 3-dimensional models of the workplace. Human engineering concepts can be incorporated for assessing body clearances, visual restrictions and performance of reach tasks. The tool is appropriate for using standardized evaluation protocols and yields numeric output [17-19]. These capabilities were considered necessary to fully explore the anthropometric limitations of the CF crew station geometries.

To obtain these capabilities, a 3-dimensional modelling software package called SAMMIE (System for Aiding Man-Machine Interaction Evaluation) was chosen [20]. SAMMIE was developed in the late 1960's and early 1970's at the University of Nottingham, U.K. [21]. A modified version of the program, available from Prime Computer Limited, provides the platform for the ACCE evaluation technique.

SAMMIE uses 3-dimensional solids modelling and computer graphics to build and display a human-model (or manikin) within a physical workplace model (Figure 1). The SAMMIE *manikin* is composed of body segments (e.g., head, neck, upper arm, thigh, calf). Segments are defined using data tables that dictate link lengths, segment shapes (depths and breadths), joint angle constraints (movement limitations), and relative joint positions (posture). These tables can be customized to model specific individuals or represent data from various populations. Once a manikin is generated, its body shape and link lengths can be modified individually or according to percentiles calculated from the data tables. Movement of individual links is under the control of joint constraint data which may be changed to simulate various effects (e.g., normal human postures, restrictive clothing).

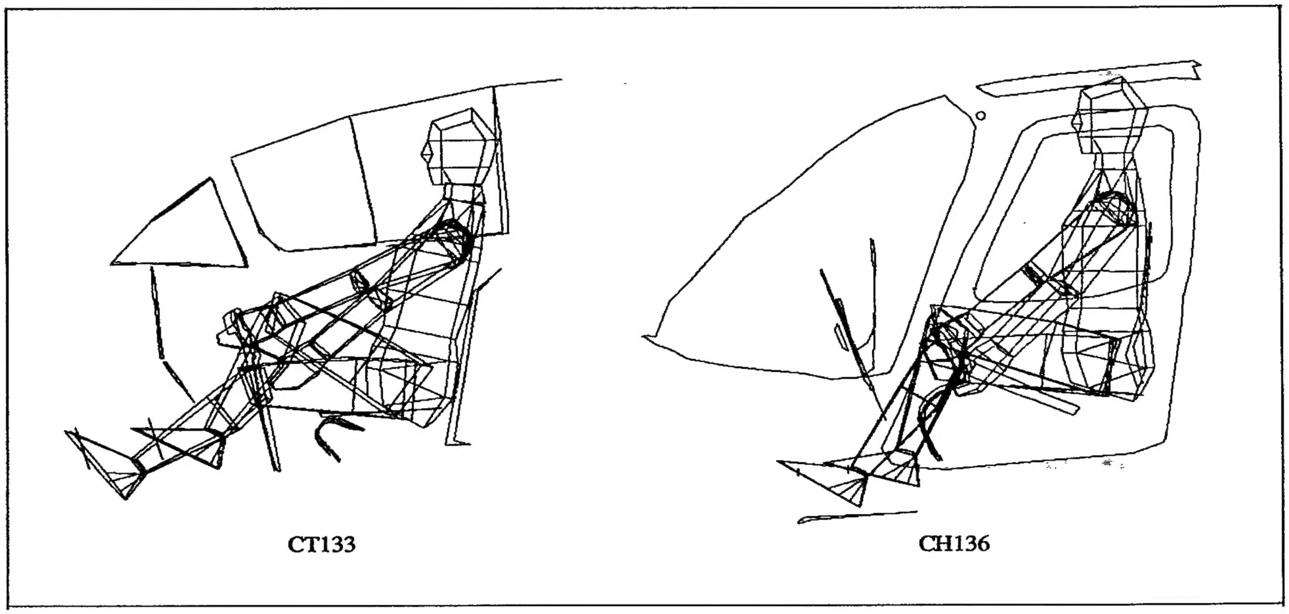

Figure 1. Graphic display of computer manikins in SAMMIE models of CT133 and CH136 aircraft.

The SAMMIE *workplace model* is composed of entities that are built from 3-dimensional primitive shapes (e.g., boxes, cones, cylinders) or irregular solids. Spatial and hierarchical relationships of the entities determine their orientations in the environment. Logical relationships among components allow mechanical functions to be simulated (e.g., movement of a crew seat along ejection rails). Movements of model components can be grouped (e.g., the pilot moves with the crew seat) or can occur independently. The models can be generated interactively or created directly from a data file following off-line preparation [22,23].

SAMMIE offers several important features, most important of which are abilities to test operator reach and vision to specific points in the workplace, and to identify physical obstructions between model elements. Numeric status statements on results, including the orientation and posture of the manikin, allow meaningful evaluations of interactions with the workplace. SAMMIE's display options enhance the power of those evaluations (e.g., sight from the manikin's viewpoint, mirror reflections, simultaneous display of different views, a mesh-grid reference system, Aitoff and Mercator projections).

To ensure that SAMMIE software creates accurate models and contains valid algorithms, the system's capabilities and limitations were evaluated. This included validation of predictions of operator reach [24-26]. Although minor problems were identified, the advantages of this system far outweigh the disadvantages.

Evaluation Technique

The underlying philosophy of ACCE is that anthropometric limitations can be found by (a) defining a multi-dimensional *anthropometric space* and then (b) testing all anthropometry combinations contained in that space for *compatibility* with the crew station. Compatibility, in this case, means that all reach, vision and body clearance requirements are met in at least one *static* configuration of the seat and rudder/rotor pedals in the crew station [27,28]. This philosophy requires three types of information: (i) anthropometry dimensions (including ranges and step-sizes) to define the anthropometry space to be tested, (ii) crew station seat and pedal adjustment parameters (including ranges and step-sizes) to define the static configurations to be tested, and (iii) reach, vision and body clearance tasks and performance criteria needed to evaluate compatibility.

Anthropometry Dimensions: Seven anthropometry dimensions were selected (Figure 2). Sitting height and seated eye height were selected due to their influences on head clearance and vision, respectively. Seated acromion height, biacromial breadth and forward functional reach were selected for their interactive effects on arm reach capabilities. Buttock-knee length and seated knee height were chosen because of their interactive influences on reach to rudder/rotor pedals, and on clearance with the seat pan and front instrument panel. Theoretically, each dimension can range from zero to the maximum allowed by the crew station, but such a strategy was not practical. To limit the computational effort to search for successful combinations yet ensure that the search be as independent of population data as possible, ranges for the dimensions were chosen to lie well outside the extremes of known adult populations. This was achieved by taking the minimum and maximum values cited in the NASA Anthropometric Source Book [29], and extending those ranges by several centimetres. Other techniques not described here were used to optimize the search for successful anthropometry combinations within the defined anthropometric space.

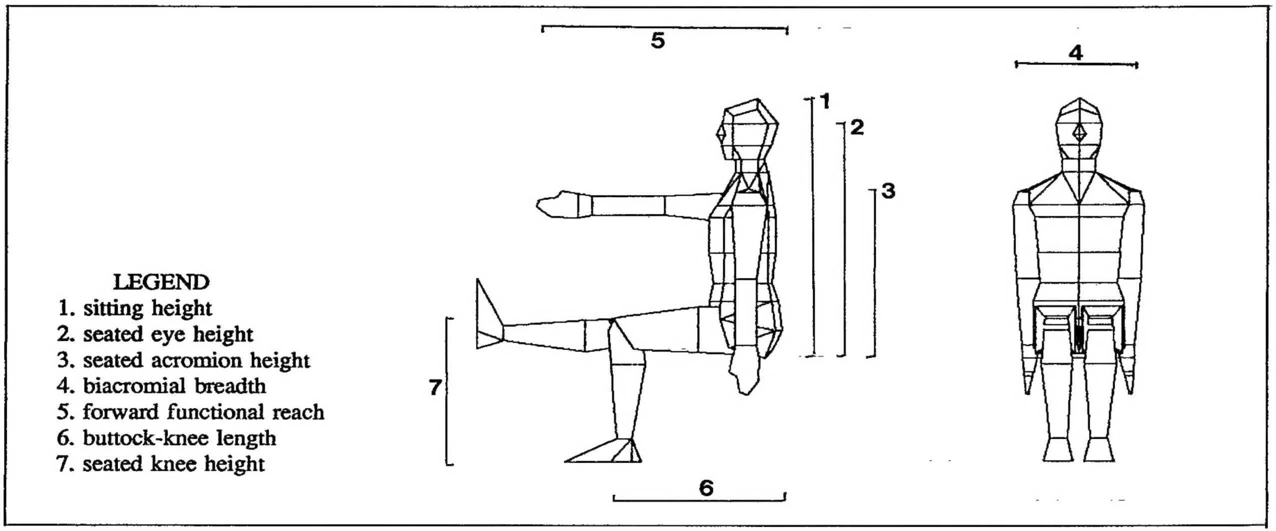

Figure 2. Anthropometric dimensions used to map the physical relationship between anthropometry and crew station geometry.

Crew Station Adjustment Parameters: These included fore-aft seat adjustment, up-down seat adjustment, and fore-aft rudder/rotor pedal adjustment. Rudder/rotor pedal deflection was treated as a sub-set of pedal adjustment; for each pedal adjustment position, reach and clearance tests were performed with pedals at full-forward, neutral and full-aft deflection. This was to ensure full use of the pedals was possible for any given adjustment position. Ranges of seat and pedal adjustment (and deflection) were taken from measurements in real aircraft.

Physical Tasks: Through group interviews with aircrew and follow-up surveys, DCIEM and CF personnel collaborated in drawing up an inventory of physical tasks for each CF crew station. Requirements for reaches, vision and body clearance under normal and emergency (e.g., ejection) conditions were considered. Tasks selected for evaluation were then described according to standard parameters (e.g., grip type, harness restraint), and performance objectives (e.g., allowable joint movements) that could be implemented using SAMMIE sub-routines.

The compatibility evaluation was implemented using SAMMIE. Its protocol resembled that of a *live* fitting trial. The crew station model was arranged with the seat full-down and full-aft, and the rudder/rotor pedals full-aft. The manikin was placed in the crew station model and assigned starting values for each of the seven anthropometry dimensions.

The manikin was subjected to a battery of compatibility tests for reach, vision and body clearance tasks (Figure 3). All tasks were of equal importance; failure to satisfy *any* task constituted incompatibility regardless of the number of successfully completed tasks. By systematically changing each of the seven anthropometry dimensions (e.g., finding minimum forward functional reach required at each combination of acromion height and biacromial breadth), the anthropometric space was searched for compatible anthropometry profiles. Those anthropometry combinations were output to a results file. The crew station configuration was then changed to represent a different seat/pedal combination, and the manikin once more was subjected to the test battery for all anthropometry combinations. This sequence was re-iterated until all crew station configurations had been tested.

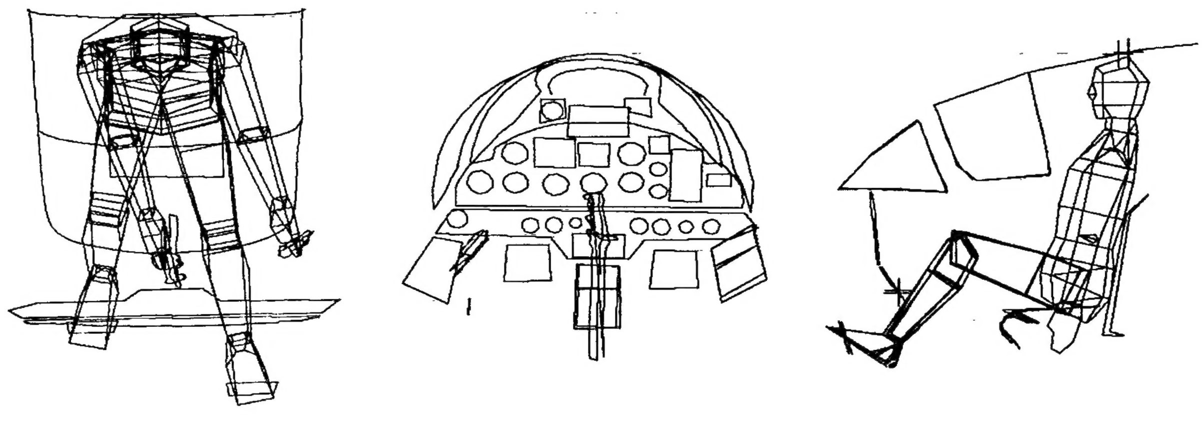

Figure 3. Physical task considerations illustrated in the CT133 aircraft.

3. METHOD

Anthropometric limitations of two CF pilot crew stations were determined. The CT133 Silver Star, a utility jet, and the CH136 Kiowa, a light observation helicopter, were selected because they are known to pose compatibility problems for both large and small individuals [12, 14]. To analyse each of the crew stations, the following activities were performed: (a) create a computer model of the crew station; (b) create and place a manikin within the crew station model; and (c) execute the evaluation protocol.

Creation of the Cockpit Model

Sonic digitization was used to collect crew station geometry information. This technology uses the time taken for sound to be received from a sound source to measure distances. Software converts these distances into X, Y and Z coordinates. Periodic checks of the data during digitizing indicated that the points collected were within 0.5 cm of their true position in the crew station [30].

The sonic digitization data were interpreted using the Automated Model Generation System (AMGENS). [31]. AMGENS is a series of computer programs written by DCIEM to convert the 3-dimensional coordinate data into a format that can be interpreted by SAMMIE. Within SAMMIE, AMGENS uses standard naming conventions to create a hierarchical, colour-coded, 3-dimensional model that can be displayed graphically. Each crew station model generated using AMGENS was examined and edited interactively to ensure it was properly formated for execution of the evaluation protocol.

Crew station seat and pedal adjustment stepsizes were set at 2 cm. For the CT133 Silver Star, this meant that 56 configurations (i.e., 7 seat positions × 8 rudder pedal positions) would be tested. For the CH136 Kiowa, which has a non-adjustable seat, this meant that 7 configurations (i.e., 1 seat position × 7 rotor pedal positions) would be tested.

Creation and Placement of the Manikin

A SAMMIE manikin was added to the crew station model with the aid of an interactive computer program. First, a manikin having prescribed body dimensions and joint constraints was created. Calculations that used seat pan angle, seat back angle and assumptions for body enfleshment dictated the location of the manikin with respect to a standard seat reference point (SRP). The manikin's posture was manipulated so that the torso was parallel to the seat back, and the line of sight was horizontal. To optimize body clearance evaluations, entities representing body enfleshment and clothing assumptions were added to the manikin. The entities used to check clearance with the seat pan were narrow planar surfaces running along the backs of the manikin's thighs. Entities used to check clearance with the front instrument panel were cylinders of appropriate diameters (i.e., enfleshment plus clothing allowance) around each of the manikin's thighs and calves.

Ranges for adjusting the manikin's anthropometric dimensions were chosen to exceed values listed in the NASA Anthropometric Source Book [29]. Sitting height, eye height, acromion height, forward functional reach, buttock-knee length and knee height dimensions were represented to a resolution of 1 cm. The resolution for biacromial breadth gave representation of a *small, medium* and *large* value on that dimension.

Execution of the Evaluation Protocol

Aircrew/Cockpit Compatibility Evaluation Protocol (ACCEP) is a set of SAMMIE computer programs that implement the evaluation strategy [32]. It manipulates aircrew anthropometry and crew station geometry parameters in order (a) to reveal and identify physical conflicts in reach, vision and body clearance requirements, and (b) to determine multi-dimensional envelopes that express the physical size limits for current CF crew stations.

For each of the CT133 and CH136 crew stations, ACCEP was run within a SAMMIE software environment on a Prime 2350 mini-computer. The output obtained using ACCEP was formated in a data base. Three types of assessment were performed; individual fit, percentage accommodation for males and females, and comparison of accommodation in the aircraft with satisfaction of CF aircrew selection criteria.

4. RESULTS

The results from ACCEP contain all possible anthropometric combinations that will fit each pilot crew station — within the described resolution limits. It is a relatively simple procedure to search this data set to determine whether a given individual has the necessary anthropometric dimensions to fit a particular crew station. A population of such individuals (measured on the appropriate anthropometry dimensions) can also be used to yield estimates of percentage accommodation. Submitting the same population to current selection standards also yields accommodation results with which comparisons can be made. For the purposes of this paper, anthropometry data for males and females were obtained from the 1967 survey of United States Air Force (USAF) male flying personnel (n=2420) and the 1968 survey of USAF women (n=1905) [33,34].

Accommodation assessments were based on aircraft requirements for head clearance, vision, leg reach and clearance and, in the case of the CT133, ejection clearance. Unless otherwise stated, arm reach requirements were not considered because of the difficulty in choosing the most *important* set of arm reach targets for a crew station. Given that CF selection standards do not consider requirements for arm reach, valuable comparisons between aircraft-imposed limitations and standards-imposed rejections could be made without consideration of this criterion.

Table 1 lists the anthropometric criteria that must be satisfied for current CF aircrew selection. Applying these criteria to the male and female USAF populations yielded acceptance figures of 94% and 36%, respectively. The high acceptance value for males is due to similarities in CF and USAF aircrew selection standards. It is anticipated that the acceptance would be lower for an unbiased male population (i.e., a population that was not pre-screened). The low acceptance value for females is understandable given the source of the CF selection criteria (i.e., originally derived from male aircrew data). Also, the female population surveyed did not undergo the same anthropometric screening as the male population, offering a partial account for the high rejection rate of the females compared to the males.

Figure 4a illustrates the percentage accommodation in each aircraft for the combined populations (males and females) as determined by the ACCEP evaluation. Seventy-five percent satisfy compatibility requirements for the CT133 jet aircraft (i.e., are able to fit in at least one seat/pedal configuration). The CH136 helicopter

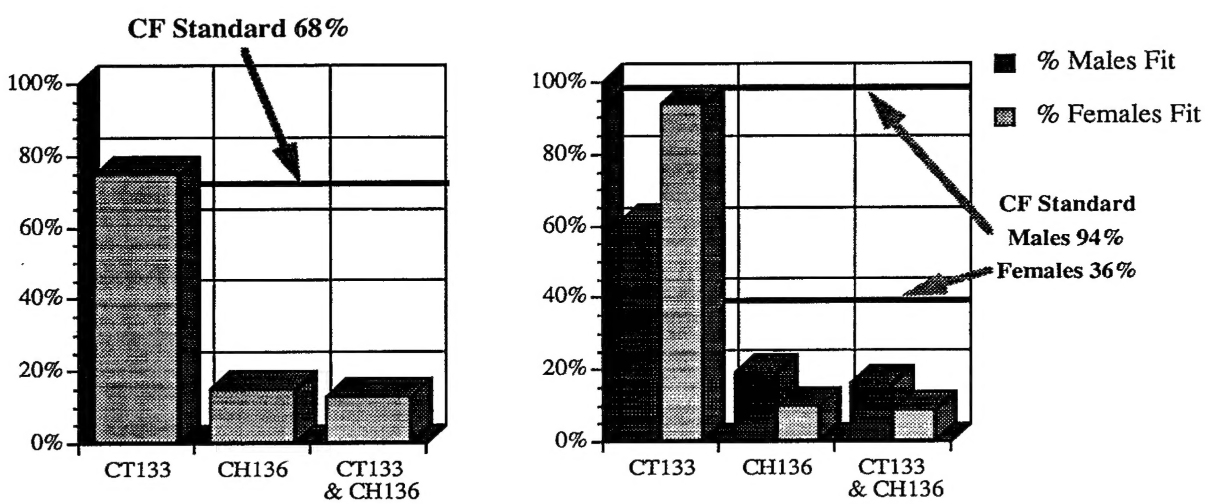

Figure 4a: combined populations (males and females)

Figure 4b: males vs. females

Figure 4. Percentage accomodation in each aircraft for the combined populations and by gender.

is considerably more restrictive, resulting in only 15% accommodation. The percentage of the combined populations able to fit both aircraft is 13%. Notice that acceptance according to CF selection standards remains constant across aircraft, at 68%.

Figure 4b presents the same percentage accommodation data, grouped by gender. Clear differences exist between males and females for the two aircraft. A smaller percentage of males (61%) than females (94%) can fit in the CT133. For the CH136, the reverse trend is observed (males 19%, females 10%). The percentages of the male and female populations able to fit both aircraft are 16% and 9%, respectively. more males (16%) Again, the CF selection standards bear little relationship to aircraft type or to gender differences.

Figures 5a and 5b illustrate reasons behind the gender differences observed in Figure 4b. Accommodation percentages for males and for females are plotted to show the additive effects of the compatibility criteria. For the CT133 (Figure 5a), differences between males and females are largely due to head clearance requirements. Females, being shorter than males, experience fewer problems hitting the canopy (99% fit for females versus 66% fit for males). Females also experience fewer problems hitting the knees on ejection. For the CH136 (Figure 5b), incompatibility problems are different. Again, females do better than males for head clearance (99% fit versus 54% fit). However, females undergo a much larger additional rejection (89%) than do males (35%) due to leg accommodation problems — relatively long legs are needed to reach the rotor pedals in the CH136. Vision is not a problem in either the CT133 or CH136 aircraft because of the large cockpit surfaces devoted to windows. These results contrast strongly with accommodations according to CF selection criteria. The CF criteria reject a significant number of females on the basis of sitting height (60%), yet reject relatively few on the basis of leg length measures (26%).

Results obtained for the CT133 and the CH136 also illustrate gender differences in accommodation among upper- and lower-body dimensions respectively. For the CT133, Figures 6a to 6d show the bivariate frequency distribution for sitting height and forward functional arm reach for the combined population (males and females). The associated bar graphs represent the percentages of males and females who meet specified accommodation requirements.

Figure 6a shows the combined population (males and females) with no restrictions imposed — hence both males and females show accommodation of 100%. Figure 6b illustrates the effect of requiring the sample to satisfy head clearance requirements for the CT133. Lightly shaded areas represent individuals who are able to fit the CT133 whereas darkly shaded areas represent individuals who are not. The bar graph demonstrates that males are more affected than females (as was seen in Figure 5a). Figure 6c shows the accommodation/rejection results that combine head clearance and the minimum arm reach needed to reach a single target in the CT133 — the compass switch (the compass switch was chosen for illustration purposes because approximately 50% of the combined population could reach it). As can be seen from Figure 6c, sitting heights and arm lengths necessary to reach the compass switch are not linearly related. Also, females are much more affected by this restriction than males (a drop of accommodation by 45% for females versus 10% for males). Again, the higher rejection rate for females is due to the combined effects of females being smaller than males, and the pre-screening of the male population. Figure 6d represents the effect of the CF standard for minimum and maximum allowable sitting heights (recall that the standard does not give arm reach requirements). It is clear from this figure that the CF selection standards are too simplistic. Although approximately the same percentage of females are rejected as shown in Figure 6c (ACCEP criteria for head clearance and arm reach), the reasons for rejection are inappropriate. Females are rejected on the basis of seated height whereas the accommodation problem is based on functional arm reach.

Results for the CH136 are used to illustrate lower-body dimension interactions. Figures 7a to 7c show the bivariate frequency distribution for buttock-knee and popliteal height for the combined populations. The associated bar graphs represent the percentages of males and females who meet requirements for leg reach and clearance. Figure 7a shows the entire population with no restrictions imposed — as for Figure 6a, both males and females show 100% accommodation. Figure 7b shows the combined effects of leg reach and leg clearance on lower-body accommodation. The lightly shaded areas represent individuals who fit in the crew station. Darkly shaded areas indicate individuals who have reach and/or clearance problems. The bar graph shows the dramatic effect that leg accommodation requirements have on females (89% rejection); males are affected to a lesser degree (51% rejection) (recall Figure 5b). Figure 7C shows the portion of the population affected by CF selection limits for buttock-knee length and buttock-heel length. The disparity between results shown in Figures 7b and 7c is a clear indication that, for the CH136, the CF selection criteria are too liberal.

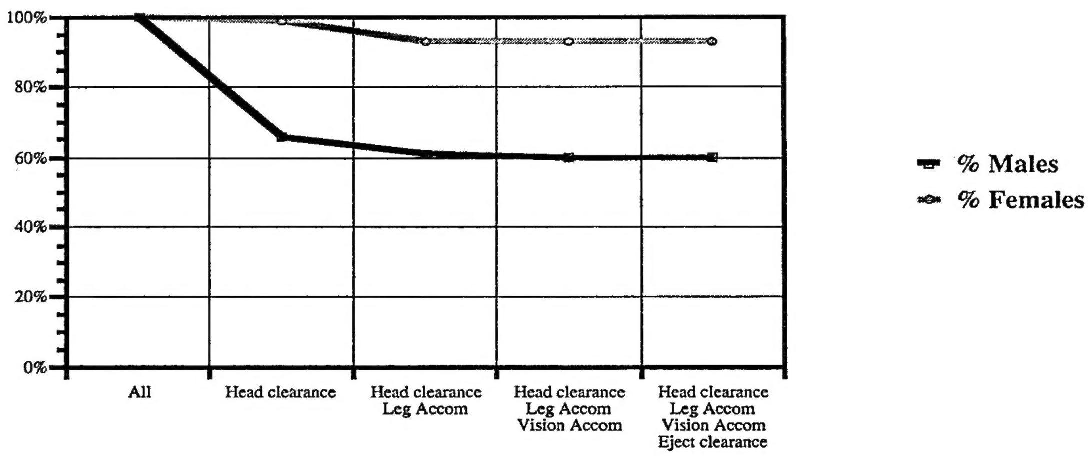

Figure 5a. Additive effects of compatibility criteria on percentage accomodation for the CT133.

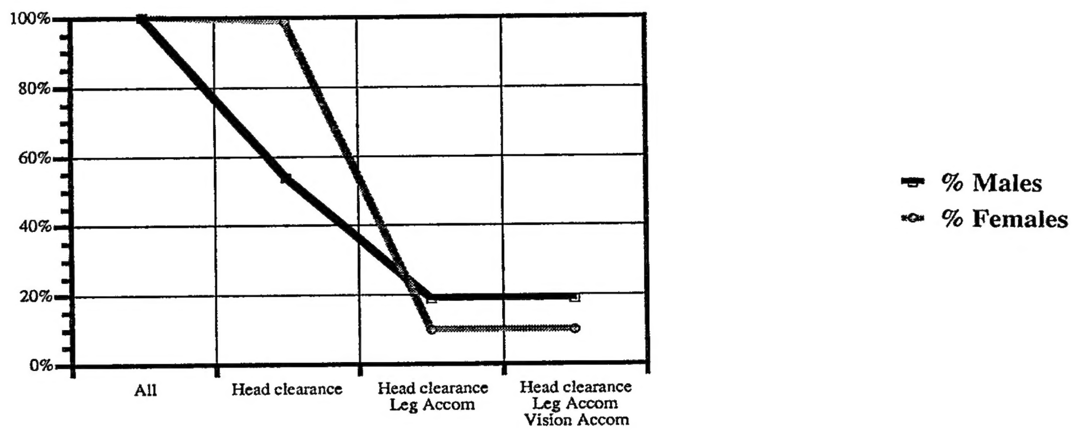

Figure 5b. Additive effects of compatibility criteria on percentage accomodation for the CH136.

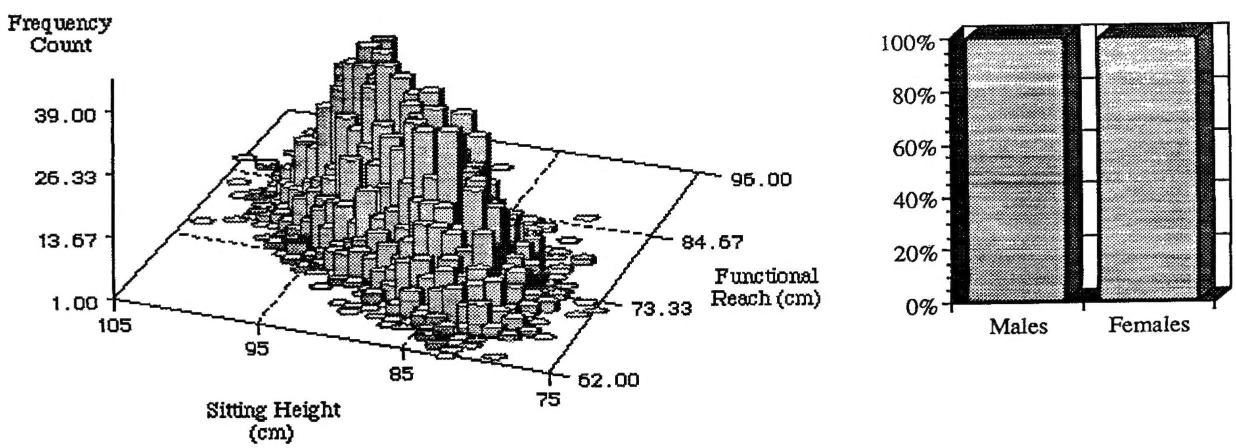

Figure 6a. No restrictions imposed.

Figure 6a. Frequency distribution for sitting height and forward functional reach, indicating regions of acceptance and rejection according to specified accommodation requirements for the CT133. Bar graphs indicate percentages of males and females meeting acceptance.

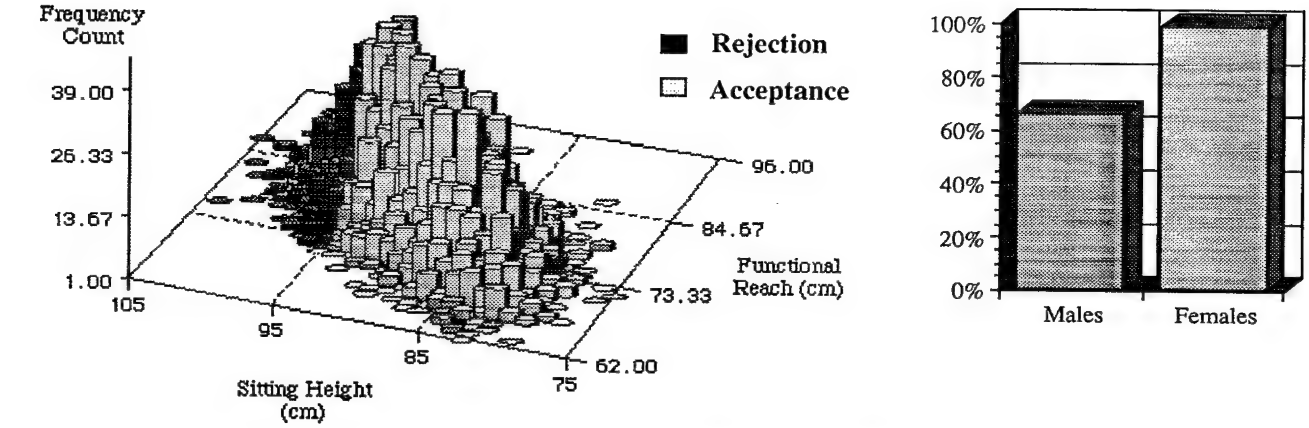

Figure 6b. ACCEP head clearance requirement.

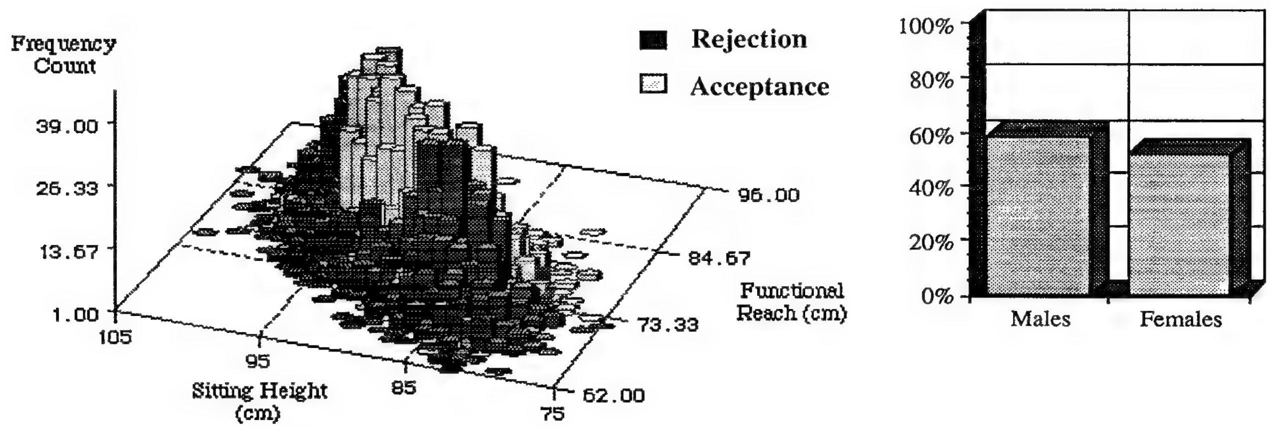

Figure 6c. ACCEP head clearance and minimum functional arm reach requirements.

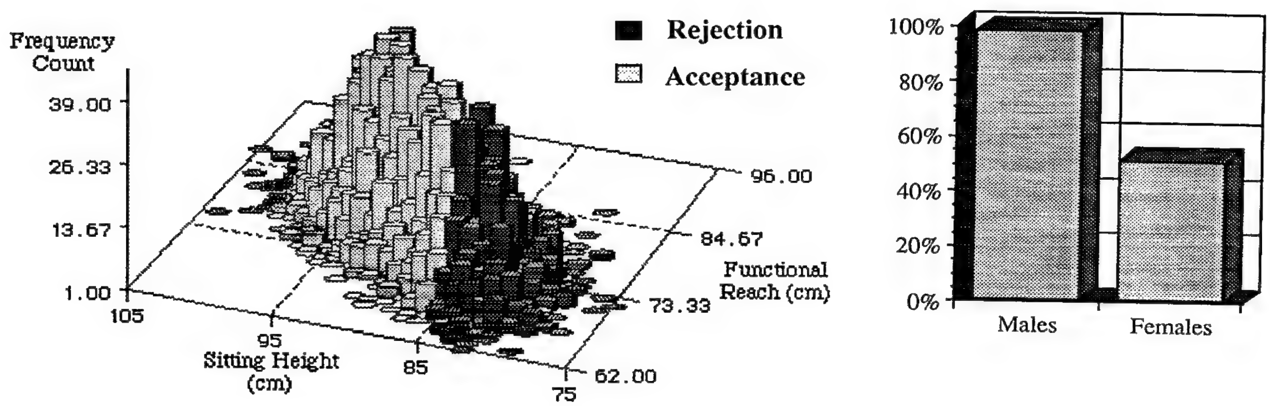

Figure 6d. CF standard for sitting height.

Figures 6b to 6d. Frequency distribution for sitting height and forward functional reach, indicating regions of acceptance and rejection according to specified accommodation requirements for the CT133. Bar graphs indicate percentages of males and females meeting acceptance.

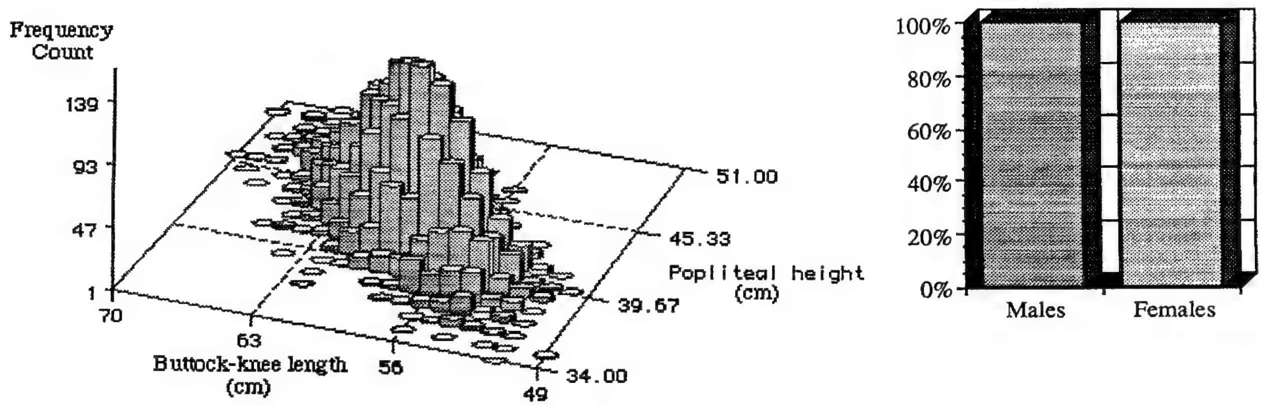

Figure 7a. No restrictions imposed.

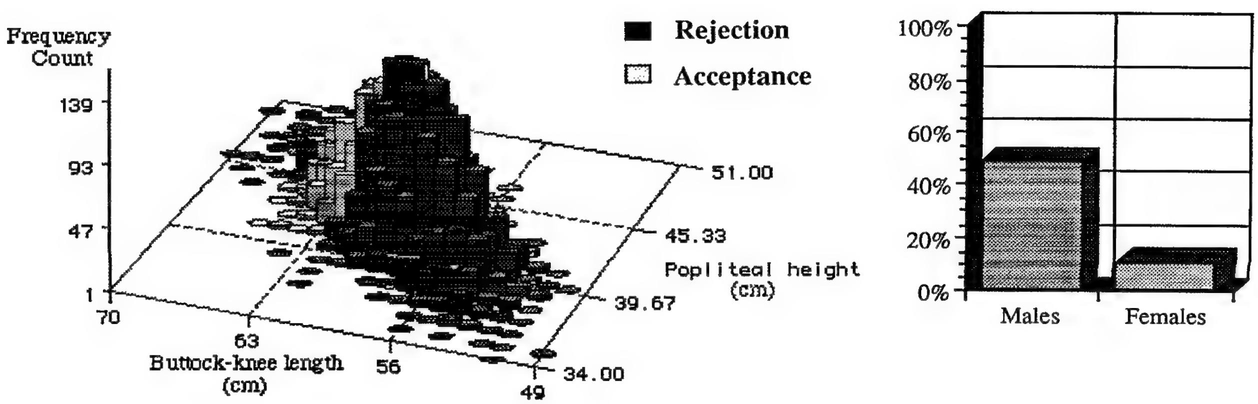

Figure 7b. ACCEP leg reach and leg clearance requirements.

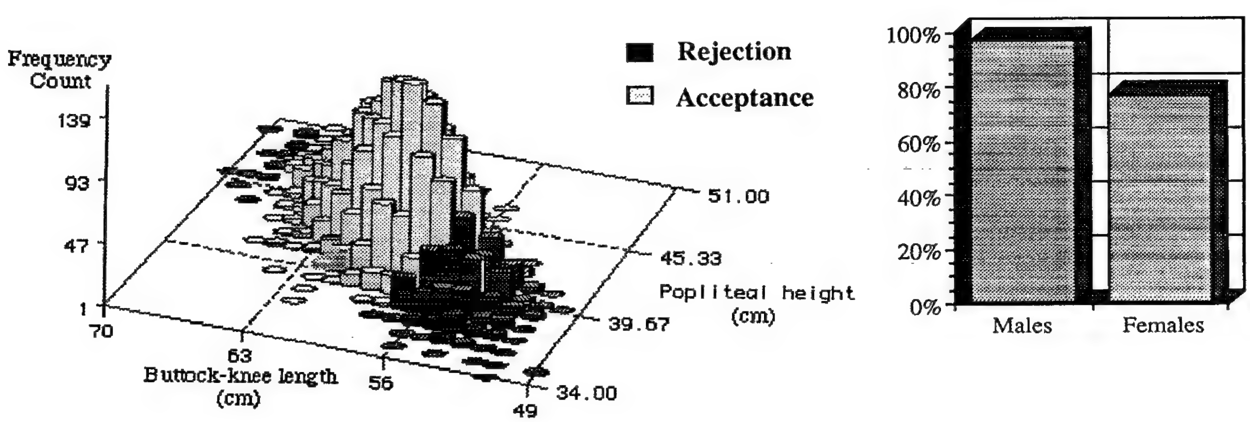

Figure 7c. CF standards for buttock-knee length and buttock-heel length.

Figure 7. Frequency distribution for buttock-knee length and popliteal height, indicating regions of acceptance and rejection according to specified accommodation requirements for the CH136. Bar graphs indicate percentages of males and females meeting acceptance.

5. DISCUSSION

This paper discusses a study done to determine the anthropometric limitations imposed by the pilot crew stations of the CT133 utility jet and CH136 light observation helicopter. Results of the study offer interesting observations on the accommodation of females in each of the aircraft. To complete the study, ACCEP was employed to manipulate anthropometry and crew station geometry parameters in a computer-modelling environment. Physical conflicts in reach, vision and body clearance were identified and multi-dimensional envelopes expressing crew station limitations in terms of acceptable anthropometric combinations were determined. Data obtained were used to assess individual and percentage accommodation of males and females in each of the two crew stations. Criteria for compatibility included head clearance, vision, leg reach and leg clearance. Although arm reach requirement data were available, they were not considered because of the difficulty in choosing comparable sets of reach targets for the crew stations. This omission must be appreciated in interpreting the results, as arm reach requirements could have significant influence on individual and population accommodation outcomes.

It is clear from the results that the anthropometric limitations imposed by the CT133 and CH136 pilot crew stations differ. This is evident from the percentage accommodation results obtained. Whereas both aircraft have similar seated height requirements, the CH136 imposes extremely restrictive leg length requirements. These results are not surprising in that the CT133 and CH136 are known to pose physical compatibility problems for both large and small individuals. What is surprising is the number of individuals who are incompatible with these aircraft (25% rejection for the CT133, 85% rejection for the CH136). These rejection figures reflect incompatibilities of larger individuals with the CT133 and incompatibilities of smaller individuals with the CH136. A point of interest is that anthropometric accommodation in the CH136 is satisfied by a sub-set of the anthropometric space satisfying CT133 accommodation. This is shown by the very small difference (2%) in percentage accommodation for both aircraft versus the CH136 alone. Hence, the combined influences of the aircraft on percentage accommodation are such that those who fit in the CH136 are compatible with the CT133. The opposite is not true, however; many who fit in the CT133 do not fit in the CH136.

Accommodation is influenced by the relative size of the population as well as the crew station's geometry. Results of this study indicate that accommodation differs between males and females in each of the CT133 and CH136 aircraft. In the case of the CT133, head clearance poses considerable restriction for males and almost none for females. Other compatibility criteria have very little influence on either gender. Overall, female percentage accommodation is extremely high (94%) whereas male percentage accommodation is somewhat lower (61%). This is surprising given that the CT133 was designed for a male population. It is also interesting to note that both populations are best accommodated with the crew seat in its full-down position, even though the CT133 offers seat adjustability. In the case of the CH136, sitting height again poses a much greater restriction for males than for females. Leg accommodation requirements restrict both genders, but have much greater impact on female compatibility. Although accommodation of each of the male and female populations is very low (19% and 10% respectively) males have a higher percentage accommodation for that aircraft. Across aircraft, females are generally rejected on the basis of leg length measures while males are generally rejected on the basis of sitting height measures. The net effect is that the CT133 is more restrictive to the male population and the CH136 is more restrictive to the female population.

Individual and population accommodation assessments for each of the CT133 and CH136 offered a basis for comparing fit in the aircraft with satisfaction of the CF aircrew selection criteria. Results of the comparisons indicate that the CF standards are too simplistic. For one, they do not account for interaction effects such as those seen for sitting height and arm reach in the CT133, and leg reach and clearance in the CH136. Given that those evaluations were intended to provide simple examples of upper-body and lower-body interactions in isolation, it can be anticipated that the interactions required for *total-body* compatibility are still more complex. Interaction effects cannot be expressed using simple minimum and maximum values for individual anthropometic dimensions. These results also suggest that the standards must include a lower leg length measure (e.g., sitting knee height) to account for interactions with the upper leg that effect leg accommodation. The standards should also include arm reach considerations although specific recommendations must be based on further study of interaction effects of upper-body dimensions.

Perhaps the most important implication from the study is that the selection standards are biased against females (and perhaps small males). Results obtained for the CH136 provide evidence of this problem. For that aircraft, female percentage accommodation for upper-body requirements resembles percentage accommodation using the CF selection standards. Unfortunately, the two percentages represent different portions of the female population (aircraft accommodation is based on functional arm reach while satisfaction of the CF standards is based on sitting height). This contrasts with evidence of a bias in favour of large males who have head clearance problems in the CT133 yet satisfy the CF standard for sitting height. While the CF selection criteria are too restrictive for women with respect to fit in the CT133, they are too liberal with respect to fit in the CH136. However, extremely low percentages of accommodation for both males and females in the CH136 suggest that the CH136 should be treated specially: either the crew station should be modified to better accommodate aircrew or it should have its own standards for selection of aircrew. Ultimately, CF selection standards that indicate biases for or against either gender must be substantiated on the basis of limitations imposed by CF aircraft.

Through this study, the utility of employing ACCEP to map the relationship between anthropometry and crew station geometry has been demonstrated. ACCEP provides a data set within which individual anthropometric profiles can be searched against successful anthropometry combinations to fit particular aircraft crew stations. In its simple form, the ACCEP data set shows promise as a tool for selecting or rejecting individual aircrew candidates. For population evaluations, it can also be used to yield cumulative percentage accommodation results according to specified compatibility criteria. This use of the data set offers an informative means to identify anthropometric limitations that distinguish one aircraft from another. In this way, ACCEP appears to be a promising tool for looking at broader selection issues (such as pilot career planning) based on evaluations of a fleet of aircraft.

The evaluation process does not end here. Results of ACCEP depend upon mathematical assumptions that are only simplifications and approximations of reality — the computer models are only as good as the input data and modelling assumptions used for their creation and manipulation [35]. Therefore, compatibility tests using live subjects must be performed to validate anthopometry/crew station relationships before ACCEP results are implemented in aircrew selection or aircraft assignment policies.

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